Physics with high energy photons

(The *quick*silver bullet ☺)

PHENIX Focus – May 30, 2006

G. David, BNL

Overview – and rules of the game

The beauty and curse of photons, as **penetrating probes**

The basic (pQCD) processes – **colinearity**

Additional processes **in the medium**

Experiments (a not too random selection – includes *controversial* stuff,
and **not** meant to be a survey of most recent results)

Recapitulation: **discriminating** between different processes with photons

This year's PHENIX-Focus tradition: talk about context, history

I won't always let reality get in my way ☺
  - just because I talk about an interesting signal it doesn't necessarily mean
    the measurement is feasible at RHIC/PHENIX
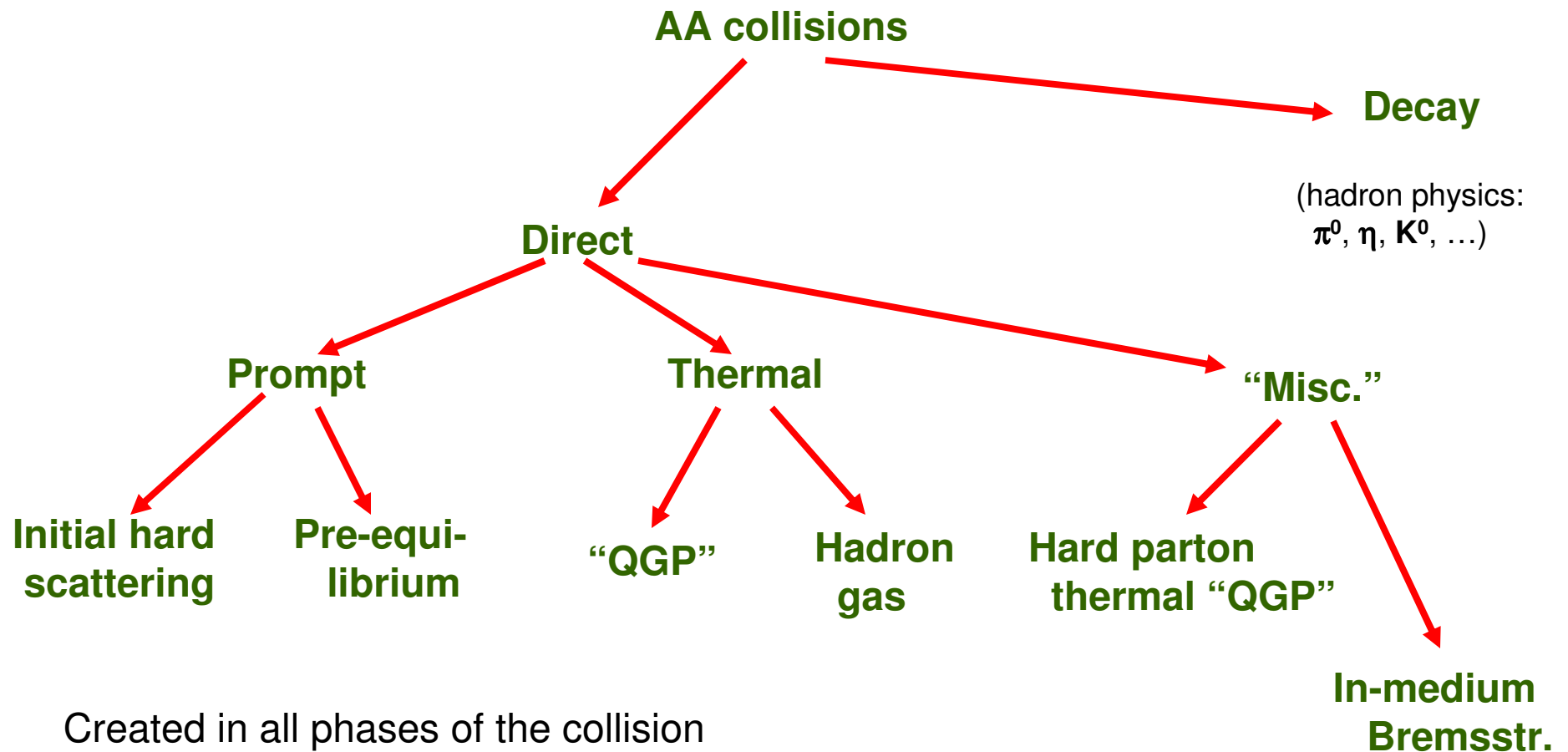 - and if it is, often it is awfully hard

I will not go into details of how inclusive, direct, isolated, *etc.* photons
  are measured (experimental techniquesdiscussed in detail in previous   PHENIX Focus talks)

Relatively little about PHENIX

Photons and photons

(A frequently used, albeit not unique terminology and hierarchy)

AA collisions

Decay

(hadron physics: π^0, η, K^0, ...)

Direct

Prompt   **Thermal**   **"Misc."**

Initial hard scattering   **Pre-equi-librium**   **"QGP"**   **Hadron gas**   **Hard parton thermal "QGP"**

In-medium Bremsstr.

Created in all phases of the collision
Once created, they survive ($\alpha_e \ll \alpha_s$) → time, temperature ... history
But this also makes measurements hard to interpret
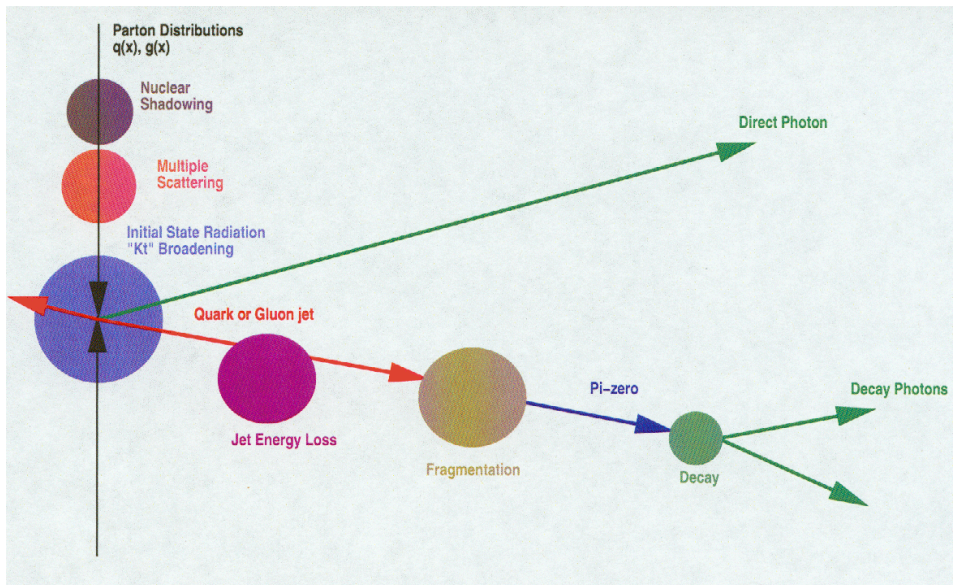
(Klaus Reygers, revisited)

Photons and collision systems

(Paul Stankus, ~1999)

A beautiful summary of the basic processes and how comparison of different signals in different colliding systems can **discriminate** between them

Some more details will be added later

	Parton Distributions q(x), g(x)	Nuclear Shadowing	Multiple Scattering	Initial State Radiation "Kt" Broadening	Jet Energy Loss	Fragmentation	Decay
A+A							
Inclusive Photons	✔	✔	✔	✔	✔	✔	✔
Inclusive Pi–Zero	✔	✔	✔	✔	✔	✔	
Direct Photons	✔	✔	✔	✔			
Photon–Pi–Zero Back to Back			✔	✔	✔	✔	
Photon–Photon Back to Back			✔	✔			
p+p							
Direct Photons	✔			✔			
p+A							
Direct Photons	✔	✔	✔	✔			

Photons and their momenta

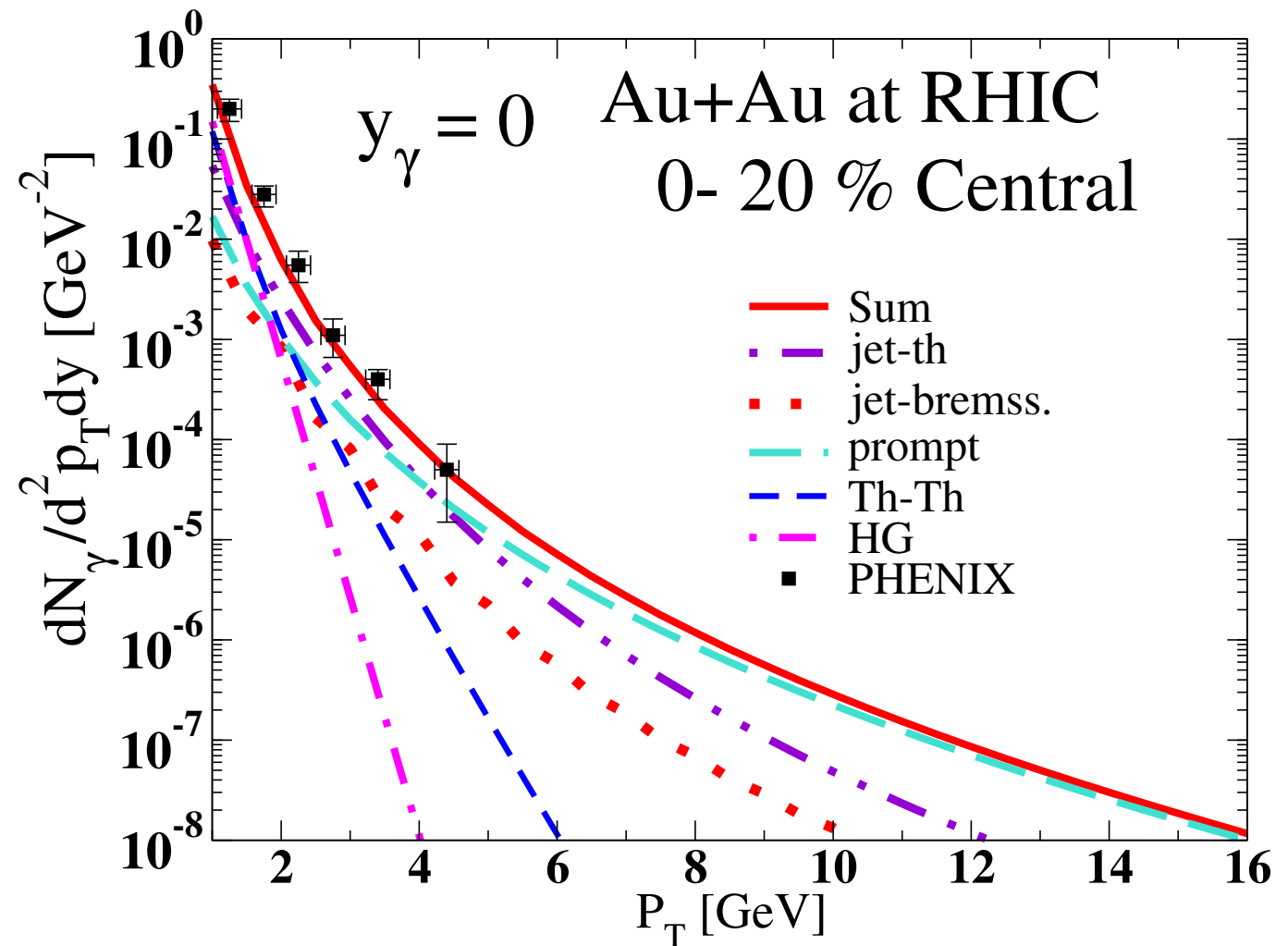Many different components known / measured / to be disentangled
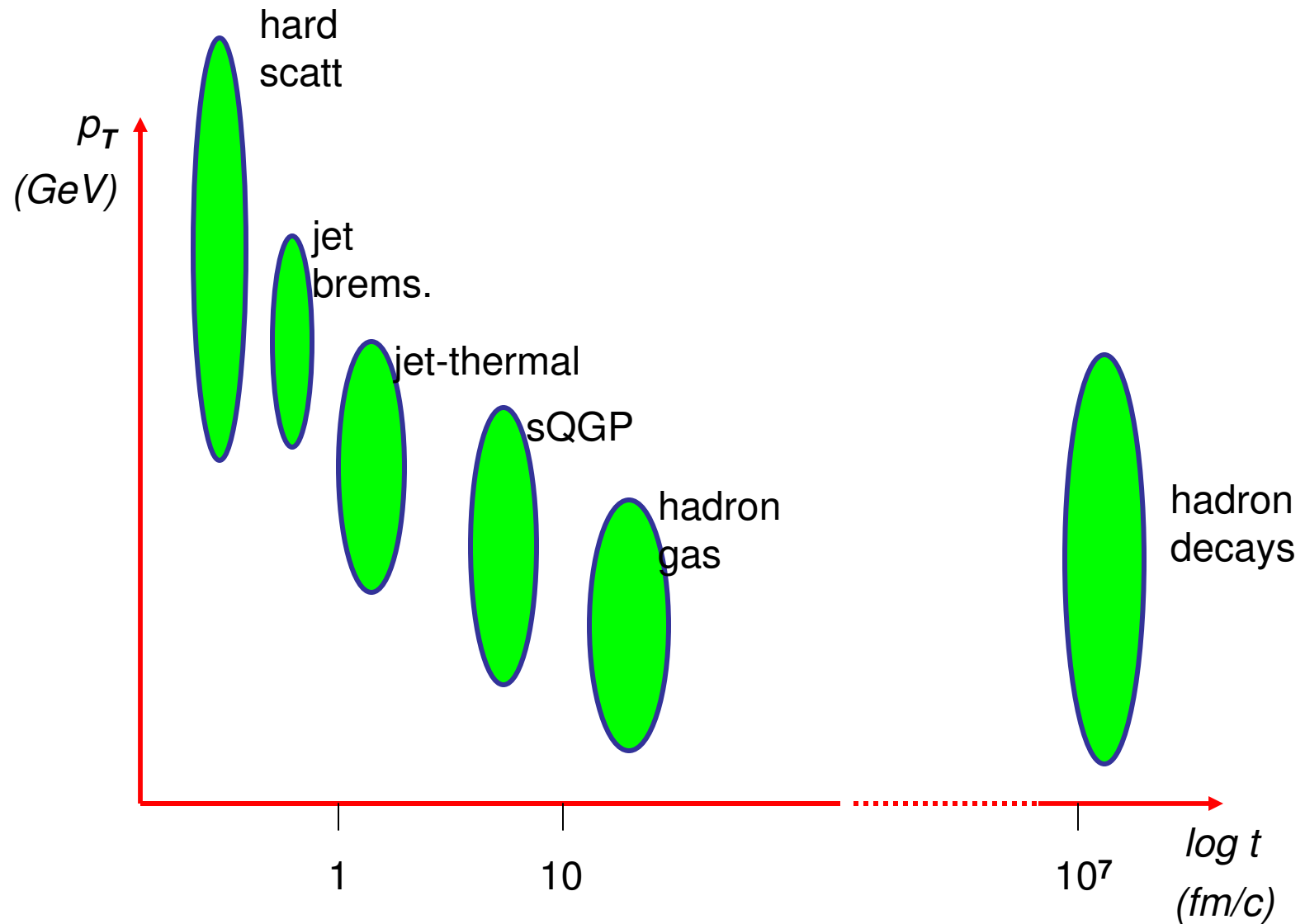
"Thermal window":
  1-3 GeV (?)
"Jet-thermal"
  3-5 GeV (?)
Hard scattering
  >6-7 GeV (?)

Photons and time history of the collision

p_T
(GeV)

hard
scatt

jet
brems.

jet-thermal

sQGP

hadron
gas

hadron
decays

1   10 10^7 *log t*
                                        (fm/c)

Direct photons: the ways to present data

For identified particles usually their spectra are shown
  - but for (inclusive!) photons this quantity is essentially meaningless
  - direct photons are the (often small) difference of inclusive – hadron decay γ
    → often large errors, particularly at lower pT

Alternative ways of presenting the data (usually smaller syst. errors):

  - $\gamma(p_T)/\pi^0(p_T)$ – often compared to the expected (simulated) γ/π under the
    assumption that all γ come from hadron decays
    → deviation from the simulated γ/π indicates direct photons

  - "double ratio": the measured γ/π divided by the expected (hadronic only) γ/π
    → excess over 1 indicates direct photons

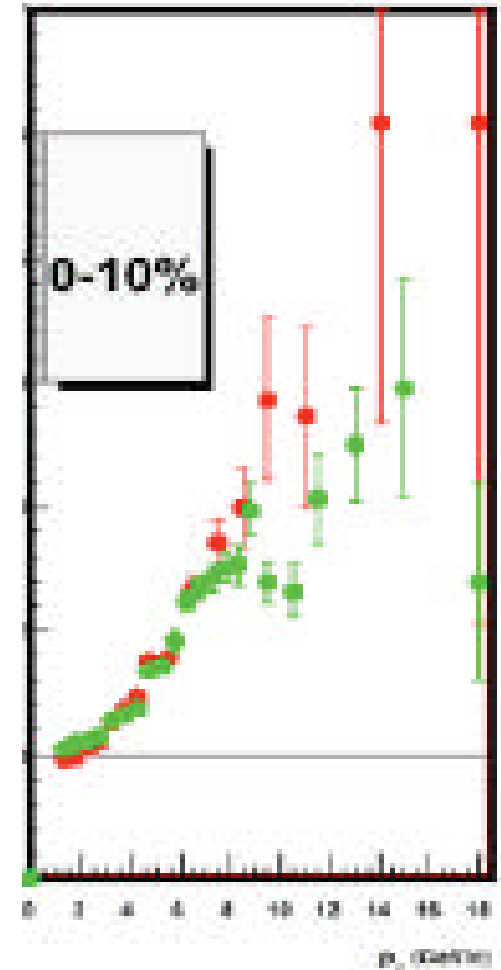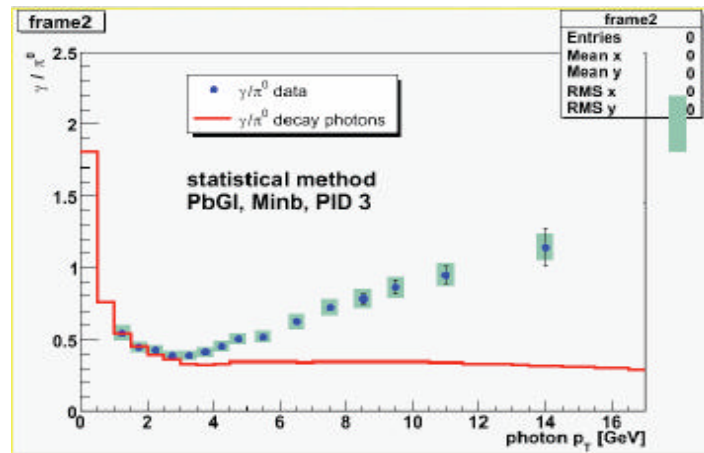Hadron suppression in heavy ion collisions helps a lot!

Direct photons: spectrum, γ/π and the "double ratio"

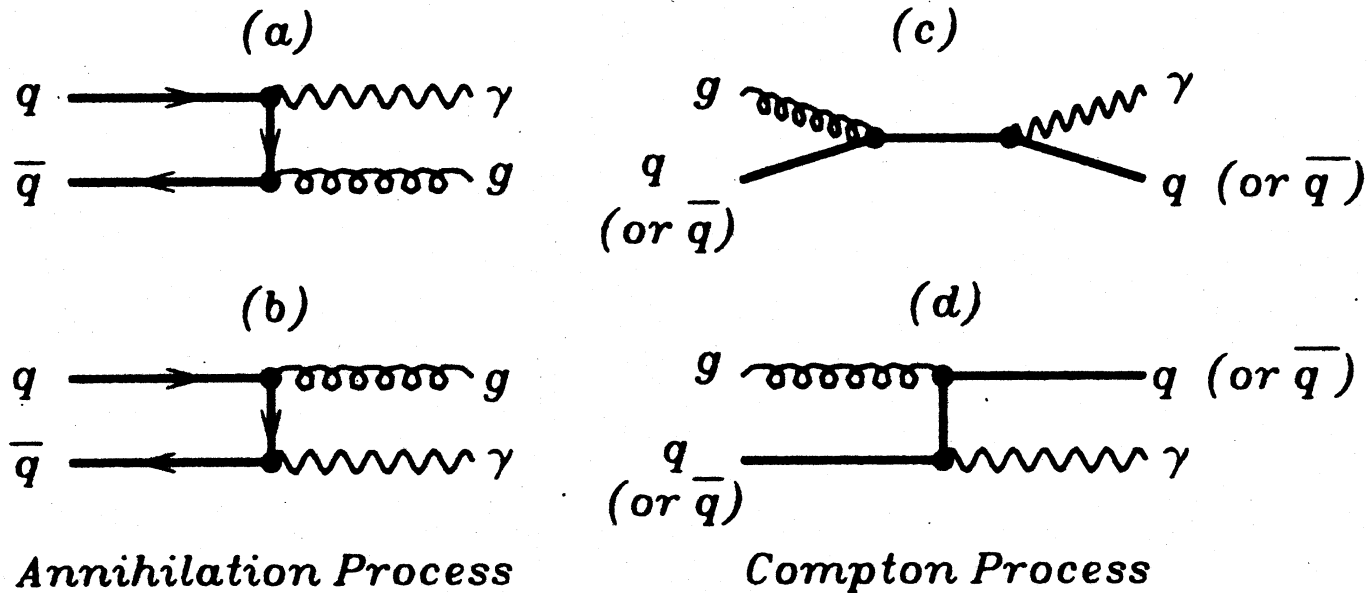Complete information, but many syst. errors
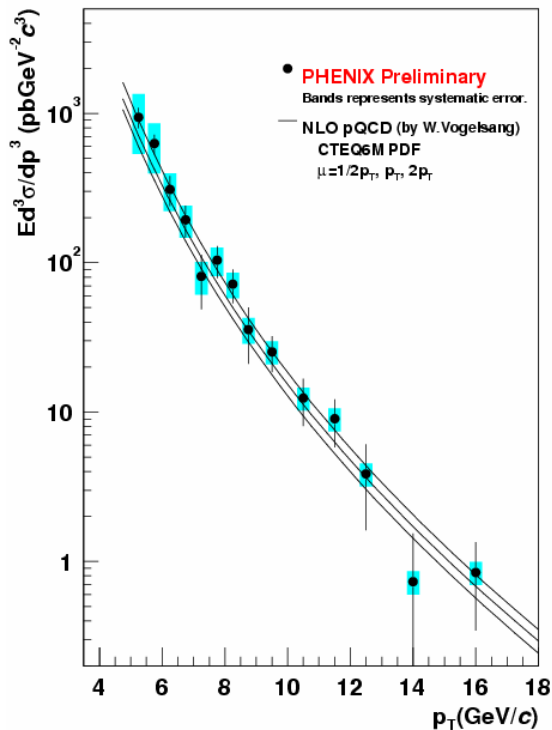
Less information, but more robust w.r.t. errors. These two presentations carry the same information

Annihilation and Compton-scattering

(a)

q γ

$\bar{q}$ g

(c)

g γ

q $q \ (or \ \bar{q})$

(or $\bar{q}$)

(b)

q g

$\bar{q}$ γ

(d)

g $q \ (or \ \bar{q})$

q γ

(or $\bar{q}$)

Annihilation Process   *Compton Process*

Mandelstam variables:

$$s = (p_1 + p_2)^2 = (p_q + p_{\bar{q}})^2 \,,$$

$$t = (p_1 - p_3)^2 = (p_q - p_\gamma)^2 \,,$$

$$u = (p_1 - p_4)^2 = (p_2 - p_3)^2 = (p_{\bar{q}} - p_\gamma)^2 \,.$$

Annihilation – direction of the photon

Cross-section, averaged over quark spins, photon,gluon polarization (allow for mass):

$$\frac{d\bar{\sigma}}{dt}(q\bar{q} \to \gamma g) = \left(\frac{e_q}{e}\right)^2 \frac{8\pi\alpha_s\alpha_e}{s(s-4m^2)}\left\{\left(\frac{m^2}{t-m^2}+\frac{m^2}{u-m^2}\right)^2\right.$$

$$\left.+\left(\frac{m^2}{t-m^2}+\frac{m^2}{u-m^2}\right)-\frac{1}{4}\left(\frac{t-m^2}{u-m^2}+\frac{u-m^2}{t-m^2}\right)\right\}.$$

which peaks when the denominators are minimum; writing them out explicitly gives

$$t - m^2 = -2p_\gamma \cdot p_q$$
$$= -2E_\gamma(E_q - |\boldsymbol{p_q}|\cos\theta_{\gamma q}).$$

$$u - m^2 = -2E_\gamma(E_{\bar{q}} - |\boldsymbol{p_{\bar{q}}}|\cos\theta_{\gamma\bar{q}}).$$

Both are minimum if θ = 0, i.e. γ lines up with either the quark or the antiquark: they are **colinear**

Expanding $(t-m^2)^{-1}$ around θ = 0

$$\frac{1}{t-m^2} \approx \frac{1}{-2E_\gamma[E_q - |\boldsymbol{p_q}| + |\boldsymbol{p_q}|\frac{1}{2}(\theta_{\gamma q})^2]}$$

$$\approx -\frac{1}{E_\gamma E_q\left[\left(\frac{m}{E_q}\right)^2 + (\theta_{\gamma q})^2\right]}.$$

giving the approximate cone size

$$\Delta\theta_{\gamma q} = \frac{m}{E_q}$$

Annihilation – energy of the photon

We've established that the most likely photon direction is collinear with the quark

The photon energy (one half of CMS energy) is

$$p_\gamma \cdot p_q + p_\gamma \cdot p_{\bar{q}} - s/2 = 0 \,.$$

where $\quad p_\gamma \cdot p_q = E_\gamma (E_q - |\boldsymbol{p}_q| \cos \theta_{\gamma q}) \,.$

In case of collinearity $\qquad p_\gamma \cdot p_q \approx \dfrac{E_\gamma}{2 E_q} m^2 \,,$

so after expanding **s** and some approximations

$$p_\gamma \cdot (p_q + p_{\bar{q}}) - s/2 \quad \approx (p_\gamma - p_q) \cdot p_{\bar{q}} + \dfrac{E_\gamma}{2 E_q} m^2 - m^2 \,.$$

Which in case of small **m** (relativistic case) leads to $\qquad p_\gamma \approx p_q \,,$

Compton-scattering

For Compton-scattering the argument is very similar to the annihilation,
   except that there is only one pole, in the **u** channel
The net result: the photon carries away most of the quark energy
   and flies out in a small cone around the original quark direction

Important note:
  - the basic processes are the same, whether it is hard scattering or QGP;
    the difference is in the relevant parton distribution functions!
  - for instance annihilation is a major contributor in QGP, but almost
    non-existent in p+p, since antiquarks are few and at small x
  - so p+p "separates out" Compton-scattering → direct photons sensitive
    to the (polarized) gluon structure functions

  - actually, this is not the entire story ☺

Photons validating pQCD in heavy ion collisions

Remember: even if we did from the beginning N_{coll} scaling of pp to establish hadron suppression in AuAu, even if we did not see suppression in dAu, it wasn't proven beyond any doubt that suppression is due to the medium.

To prove it we needed something that does not interact with the medium, and actually does scale with N_{coll} - we needed photons

Note that this is also a statement on (non)modification of PDFs
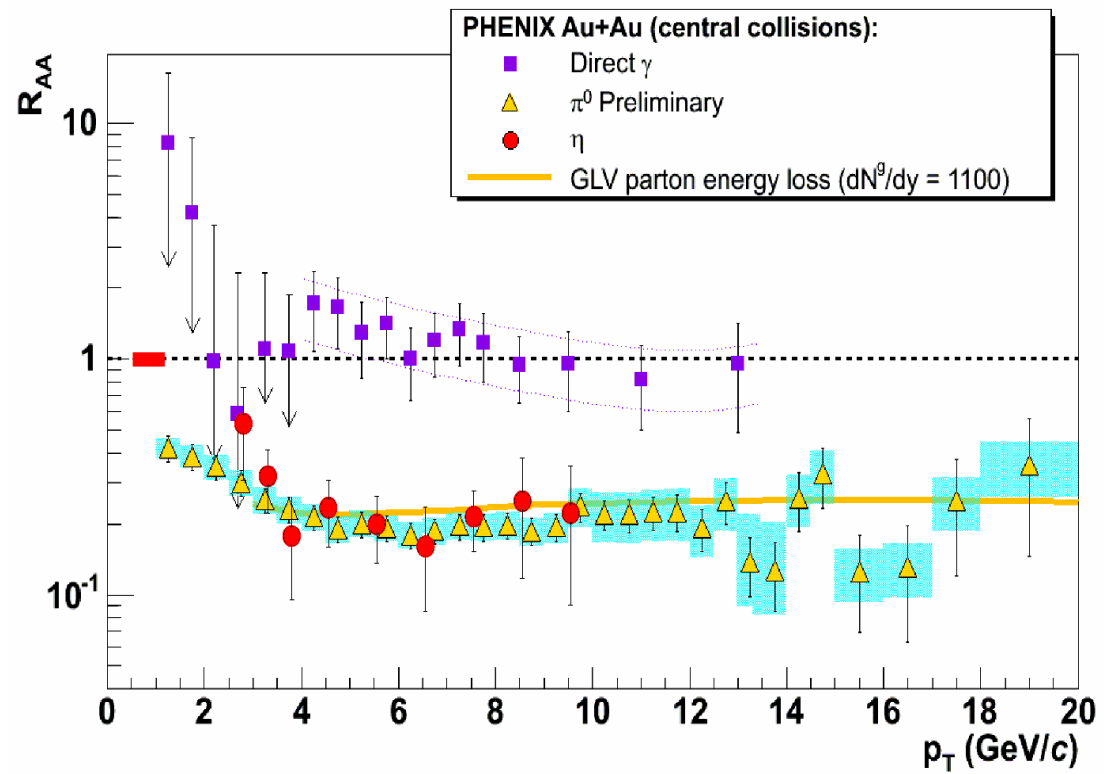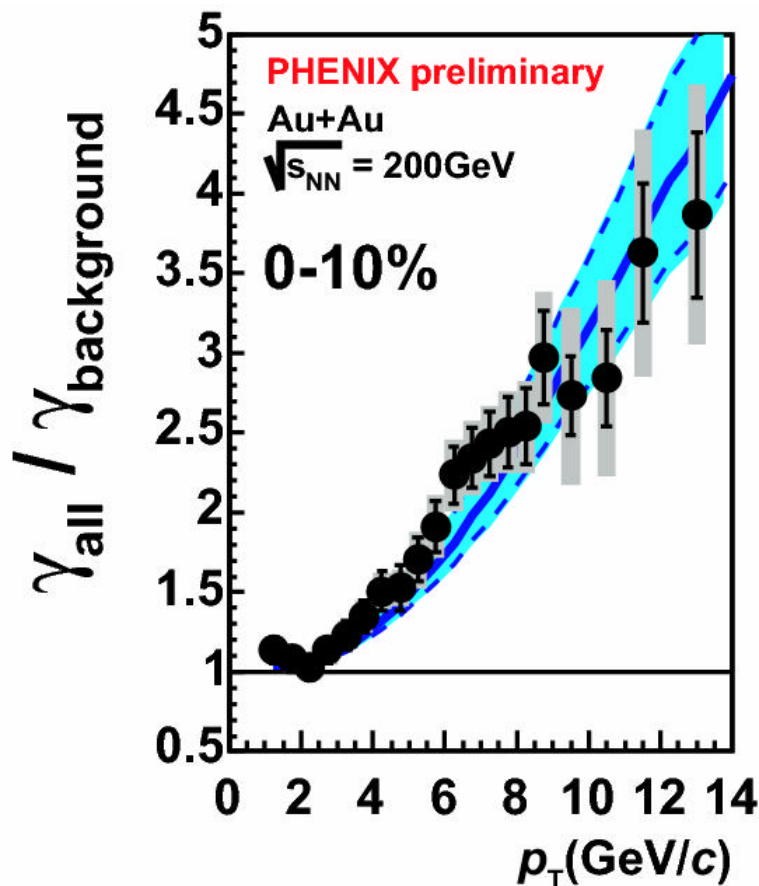
Where can pQCD be tested?
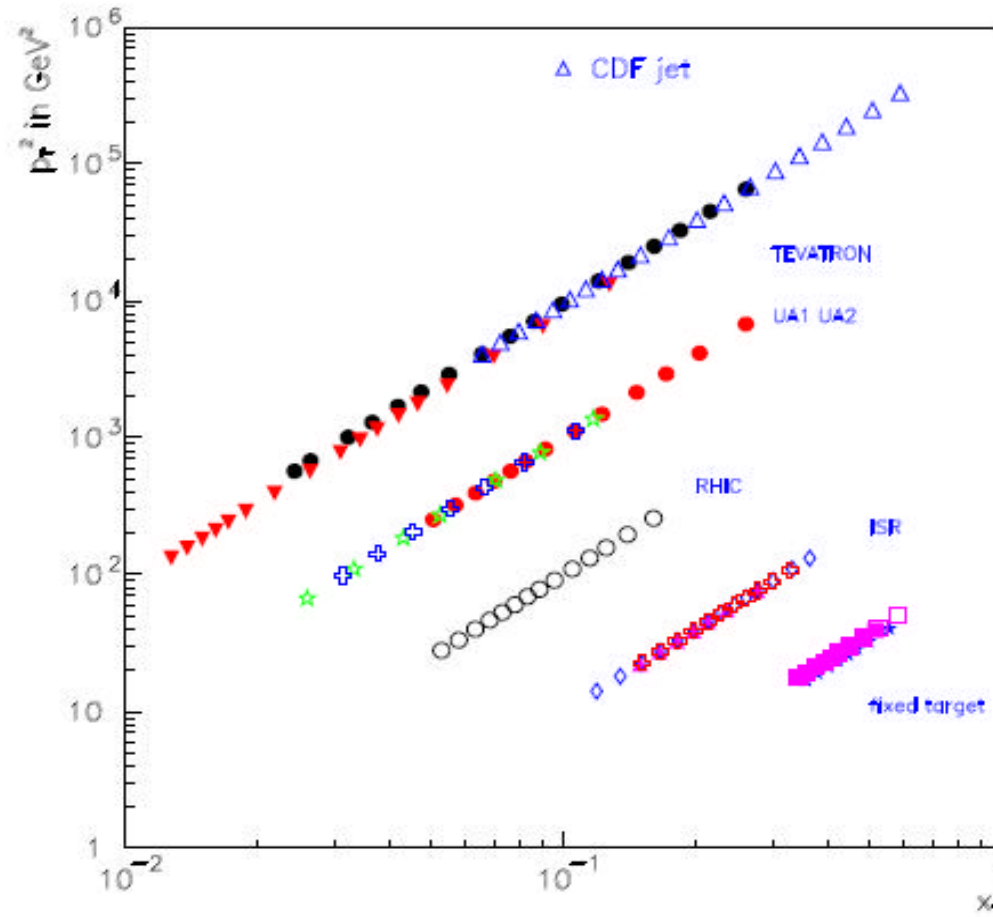
Figure 12: The kinematical region probed by prompt photon experiments compared to that relevant for jet production. Each data point is represented by a symbol as in Fig. 11 for photons, and by open triangles for jets.

hep-ph/0602133
Aurenche et al.

Test of pQCD: world data on pp vs theory

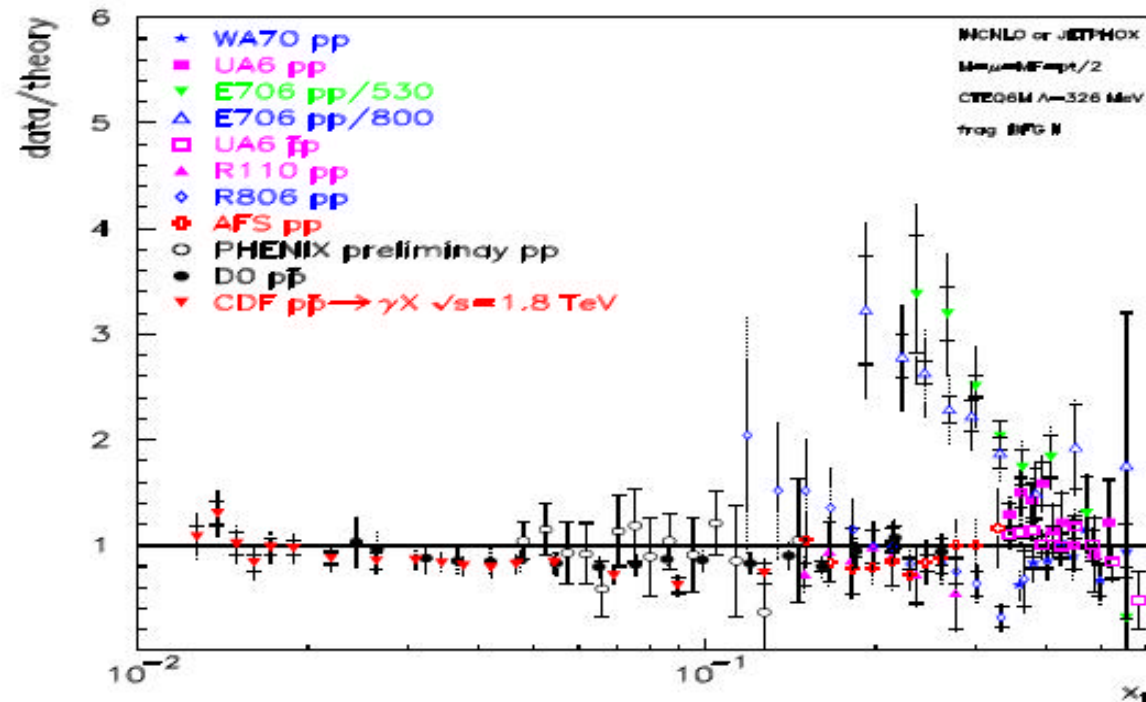NLO calculations agree with data over 9 orders of magnitude – except for one experiment

Figure 6: Ratios data/theory for collider and fixed target data with the scale $\mu = p_T/2$. For PHENIX and lower energy data the inclusive cross section is used while the isolated one is used for CDF and D0. Statistical erros only for PHENIX data.
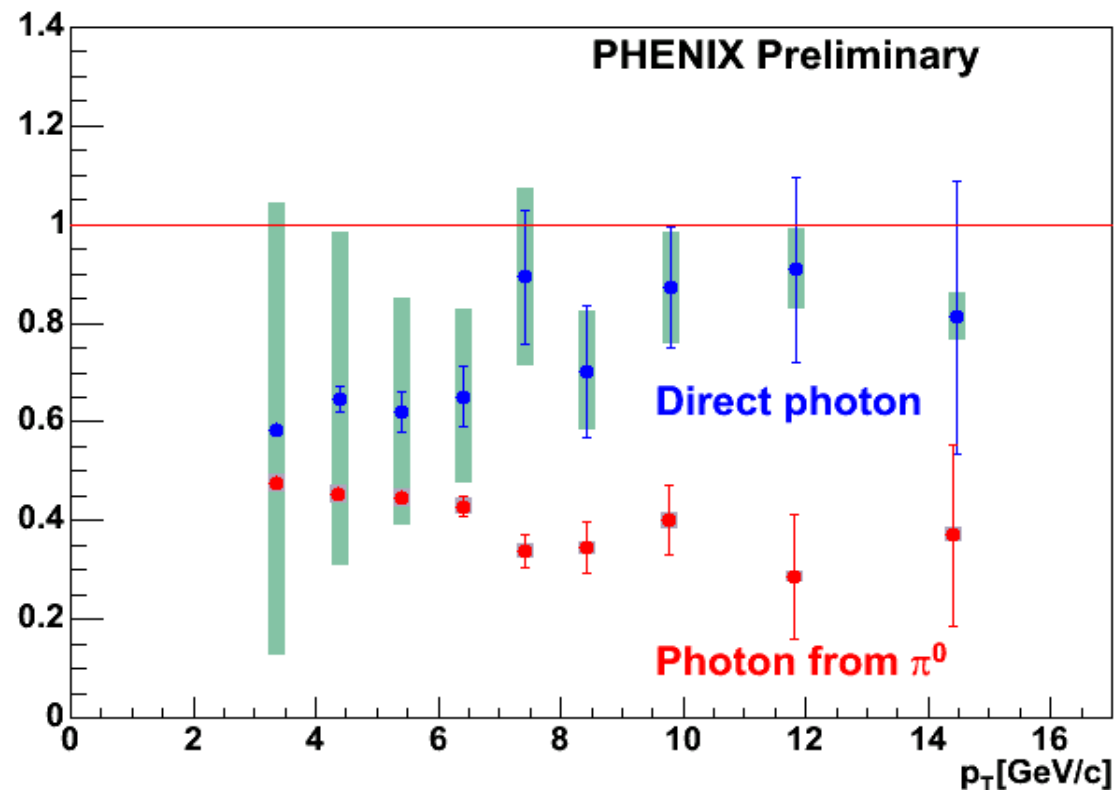
hep-ph/0602133
Aurenche et al.

Isolated / non-isolated photons

Fragmentation or
  hadronic photons
  should be accompanied
  by other particles nearby

Primordial (annihilation,
  Compton) photons should
  be isolated

Direct photon   : isolation / subtraction
Photon from π^0 : isolated photon / all

PHENIX Preliminary

Direct photon

Photon from π^0

p_T[GeV/c]

Hisa's CIPANP talk

Isolated photons: experiment vs. theory

Isolation cut

   $0.1*E\gamma > E_{cone(R=0.5rad)}$

$+$ By M.Werlen,
   JETPHOX
   $-.35<y<.35$
   $\mu=pT$
   BFG set2, CTEQ6M

— By W.Vogelsang,
   R=0.4
   $\mu=pT$, CTEQ6M

PHENIX Preliminary

Direct photon

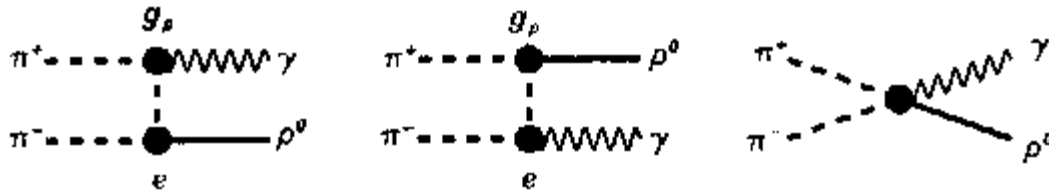p_T[GeV/c]
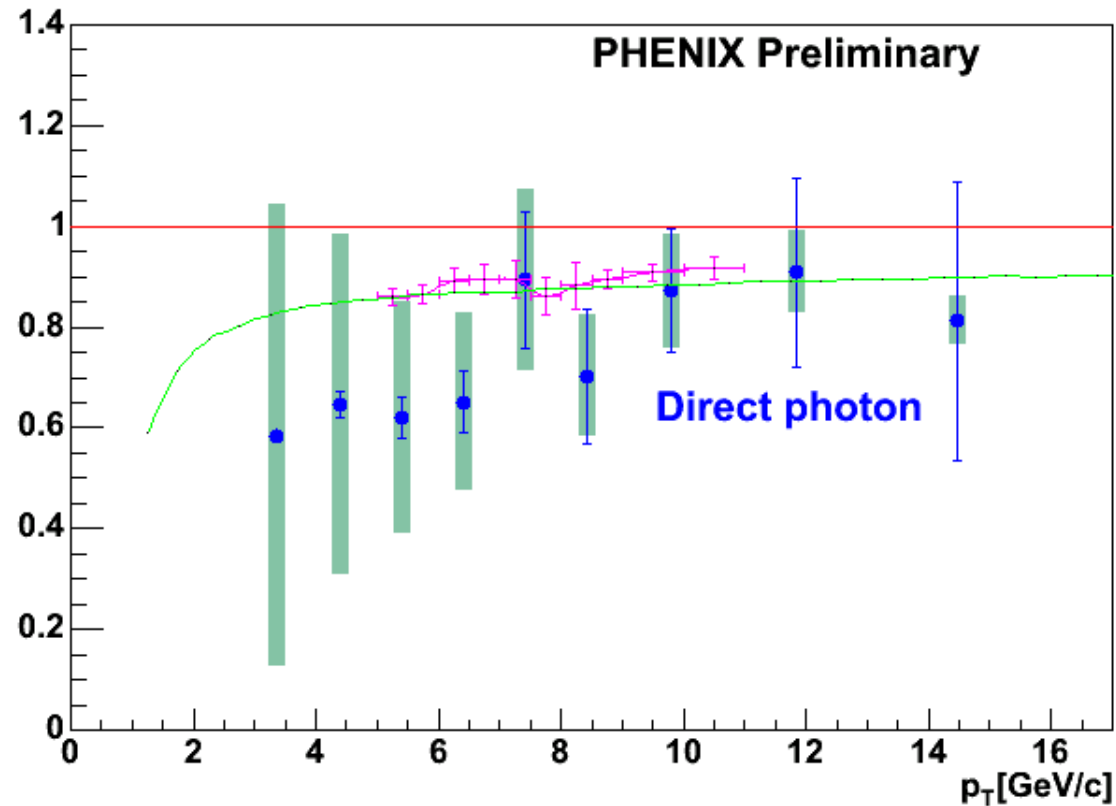
Bremsstrahlung – before and after

(a)
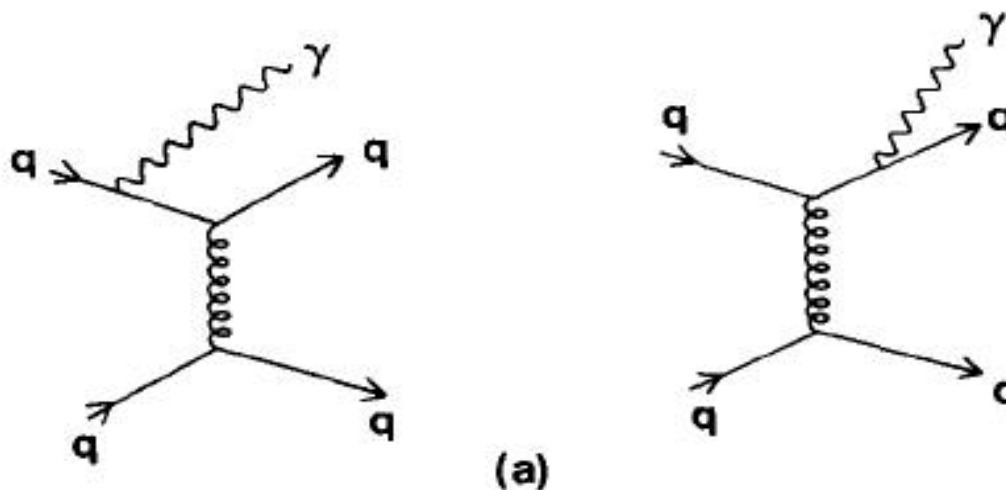
Before the interaction:
- modification of the effective PDF
- adds to the initial k_T

After the interaction:
- photons in the vicinity of the leading hadron
- enhanced in the spatially large direction (out-of-plane) → negative v_2
- modifies effective FF

Photon production from hadrons

$$\frac{d\sigma}{dt}(\pi^+\pi^- \to \gamma\rho^0) = \frac{8\pi\alpha_e\alpha_\rho}{s(s-4m_\pi^2)}\left\{2-(m_\rho^2-4m_\pi^2)\left[\frac{s-2m_\pi^2}{s-m_\rho^2}\left(\frac{1}{t-m_\pi^2}\right.\right.\right.$$

$$\left.\left.\left.+\frac{1}{u-m_\pi^2}\right)+\frac{m_\pi^2}{(t-m_\pi^2)^2}+\frac{m_\pi^2}{(u-m_\pi^2)^2}\right]\right\}. \quad (16.69)$$

$$E_\gamma\frac{d\sigma}{d\boldsymbol{p}_\gamma}(\pi^+\pi^- \to \gamma\rho^0) \approx \frac{1}{2}\sigma_{\pi^+\pi^-\to\gamma\rho^0}(s)E_\gamma[\delta(\boldsymbol{p}_\gamma-\boldsymbol{p}_{\pi^+})+\delta(\boldsymbol{p}_\gamma-\boldsymbol{p}_{\pi^-})].$$

Bottom line (Lichard, …): yield from hadron gas similar, maybe even bigger
  than from QGP ("the hadron gas outshines the plasma")
Effective photons temperature very high

Jet-photon conversion

PRL 90 132301 (2003)
(Fries, Muller)

Recall Compton-scattering:
the most probable process is that
the photon is emitted in ~ the
direction of the quark and carries
~ the entire energy of the quark
(similar story for annihilation)

In the medium a jet (anti)quark can
convert to a photon by annihilating
or Compton scattering with a thermal
gluon

Normal jets "encode" energy loss in the
entire plasma, jet-conversion photons
have only part of that (harder spectrum
than "ordinary" jets)
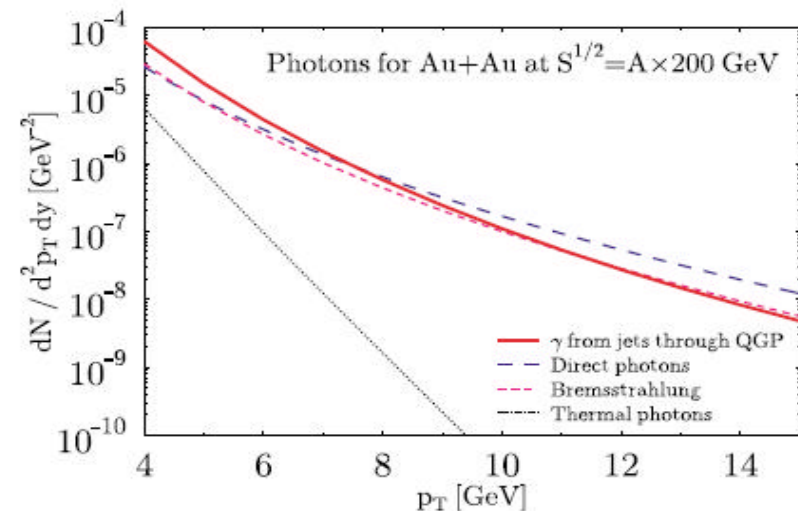
FIG. 1 (color online). Spectrum $dN/d^2 p_\perp dy$ of photons at $y = 0$ for central collision of gold nuclei at $\sqrt{S_{NN}} = 200\,\text{GeV}$ at RHIC. We show the photons from jets interacting with the medium (solid line), direct hard photons (long dashed), bremsstrahlung photons (short dashed), and thermal photons (dotted).
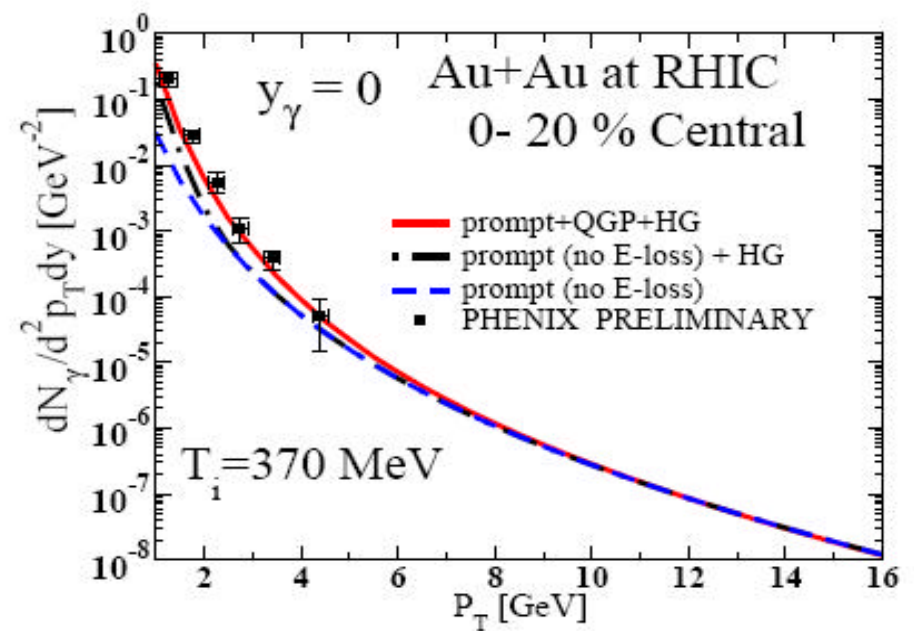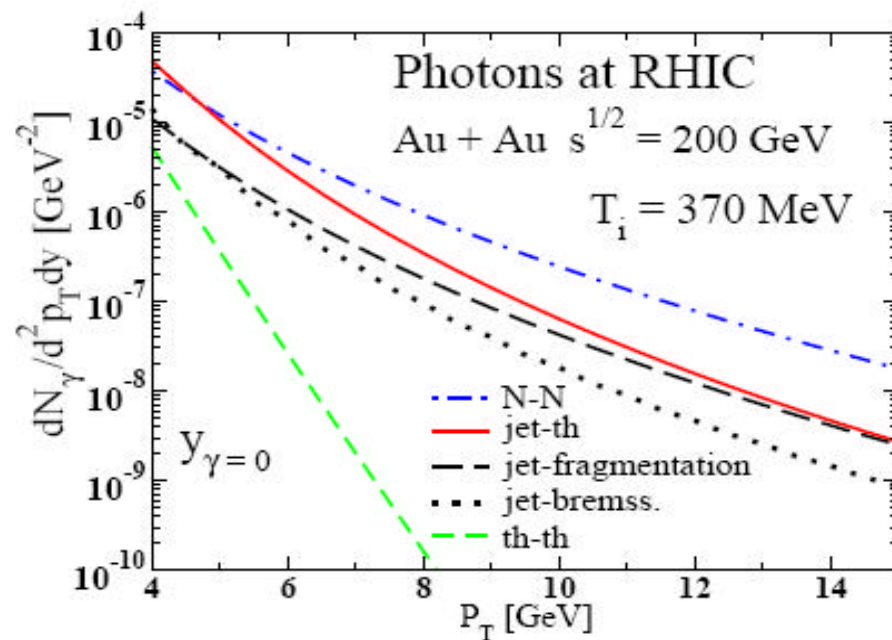
Oh, I almost forgot: thermal radiation ☺

hep-ph/0512109 (Gale)

Once upon a time this **was** the issue most talked about…

Hard to access experimentally

Phase transition

Annihilation vs. Compton (Fermilab – E706) ⬭⬭

In π^- Be annihilation is significant due
to the (-2/3 charge) valence anti-u
while it would be suppressed in π^+ Be
since anti-d is 1/3 only

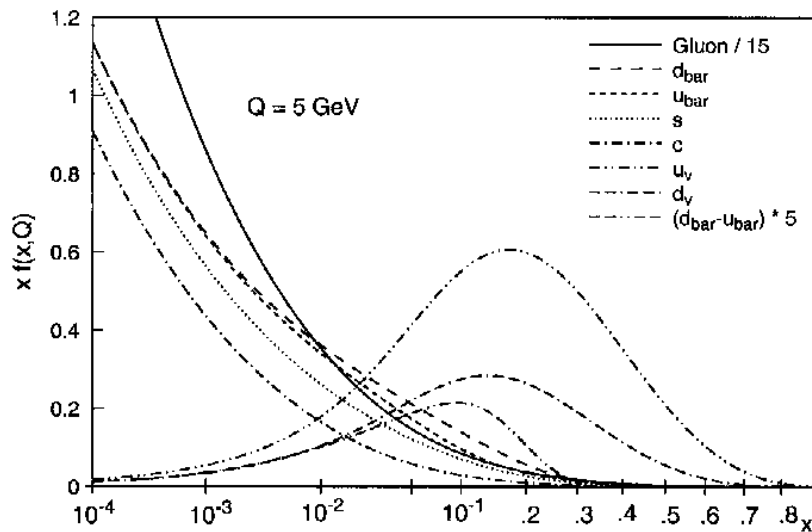In pBe you only have sea antiquarks
-> Compton dominates

Figure 2 Overview of CTEQ5M parton distributions at $Q = 5$ GeV. The gluon
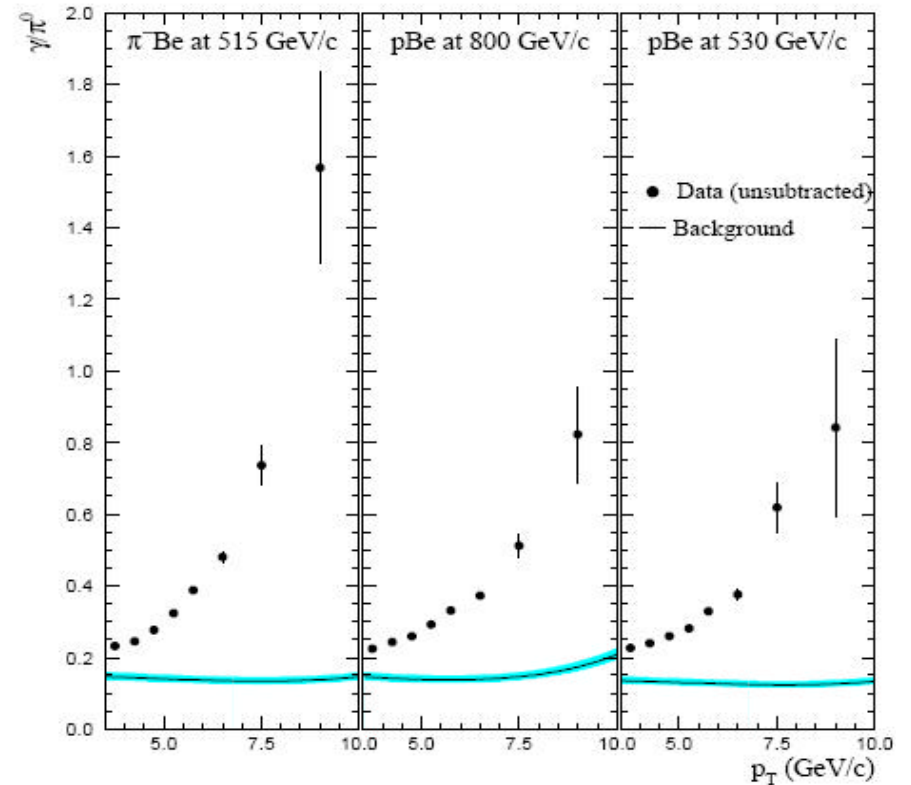distribution is scaled down by a factor of 15, and the $(\bar{d} - u)$ distribution is scaled

FIG. 21: Ratios of the $90N$ direct-photon candidate spectra to
the measured π^0 cross sections (points) compared to γ_{bckg}/π^0
from the DGS (curves) as functions of p_T for the data samples
considered in this paper. The error bars represent statistical
contributions to the uncertainties. The width of each band
around the background represents the systematic uncertainty
on that background.

Initial soft-gluon radiation? (Fermilab – E706)

PRD 70 (2004) 092009
(Apanasevich et al.)

NLO pQCD (dashed curves) does not
  describe photon production
Assuming that initial (pre-collision)
  soft gluon radiation introduces an
  effective kT, the data are well described
  (solid curves)
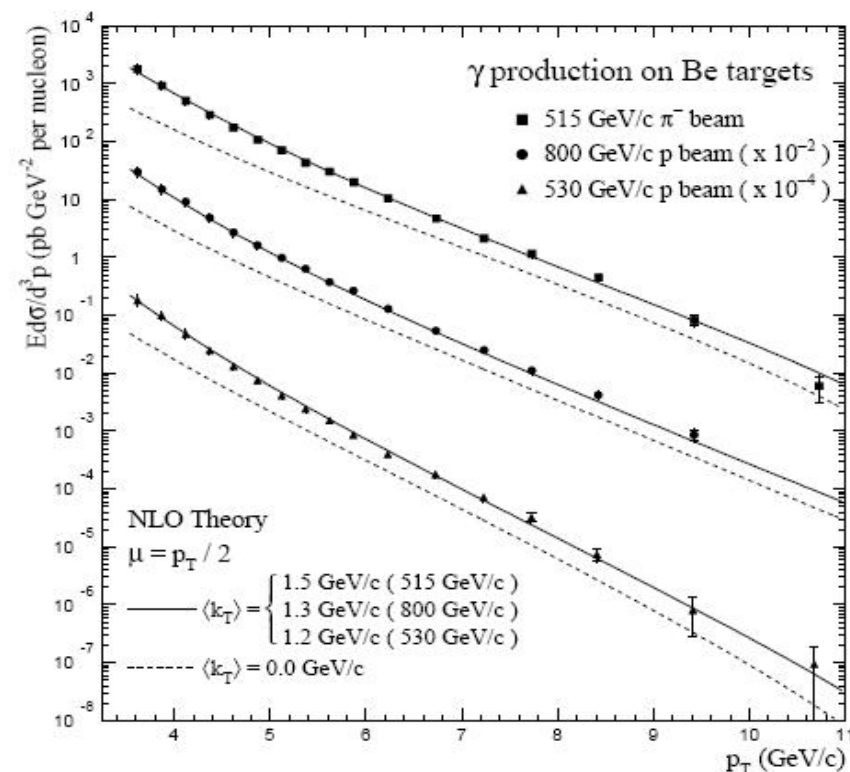No other experiment needs such k_T
  enhancement (non-perturbative)

FIG. 28: Invariant differential cross sections per nucleon for
direct-photon production as functions of p_T, averaged over
rapidity, for 515 GeV/c π^- and 800 and 530 GeV/c proton
beams incident upon beryllium. The error bars represent the
statistical and systematic uncertainties combined in quadra-
ture; the innermost interval indicates the statistical uncertain-
ties. Overlaid on the data are NLO PQCD and k_T-enhanced
NLO PQCD calculations. GRV92 PDF were used in the inci-
dent π^- calculations, while CTEQ5M PDF were used in the
incident proton calculations.

Cronin-effect in photons? (Fermilab – E706)

hep-ex/0506003
(Apanasevich et al.)

Difference between γ (initial state effect only?) and π⁰;
still if true, confusing picture
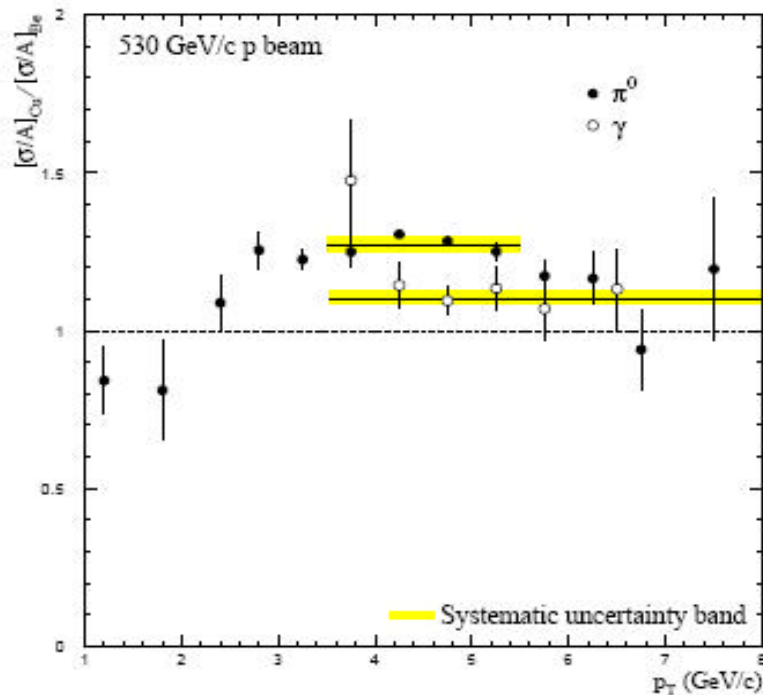

FIG. 16: The ratio of inclusive π^0 and direct-photon production cross sections per nucleon in pCu to those in pBe collisions at 530 GeV/c. Simple straight line fits to regions with relatively flat distributions have been overlaid on the data. The error bars represent only statistical contributions to the uncertainties. Systematic uncertainties are indicated by the shaded region associated with the fit.
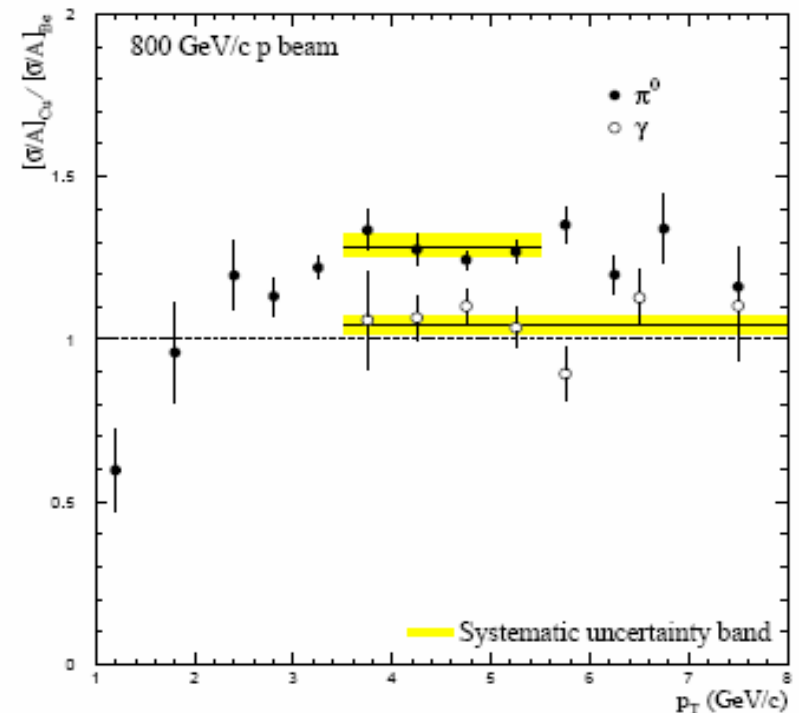
FIG. 17: The ratio of inclusive π^0 and direct-photon production cross sections per nucleon in pCu to those in pBe collisions at 800 GeV/c. Simple straight line fits to regions with relatively flat distributions have been overlaid on the data. The error bars represent only statistical contributions to the uncertainties. Systematic uncertainties are indicated by the shaded region associated with the fit.

CERN – R110

Nucl. Phys. B327 (1989) 541
(Angelis et. al, inc. MJT…)

pp at 63 GeV

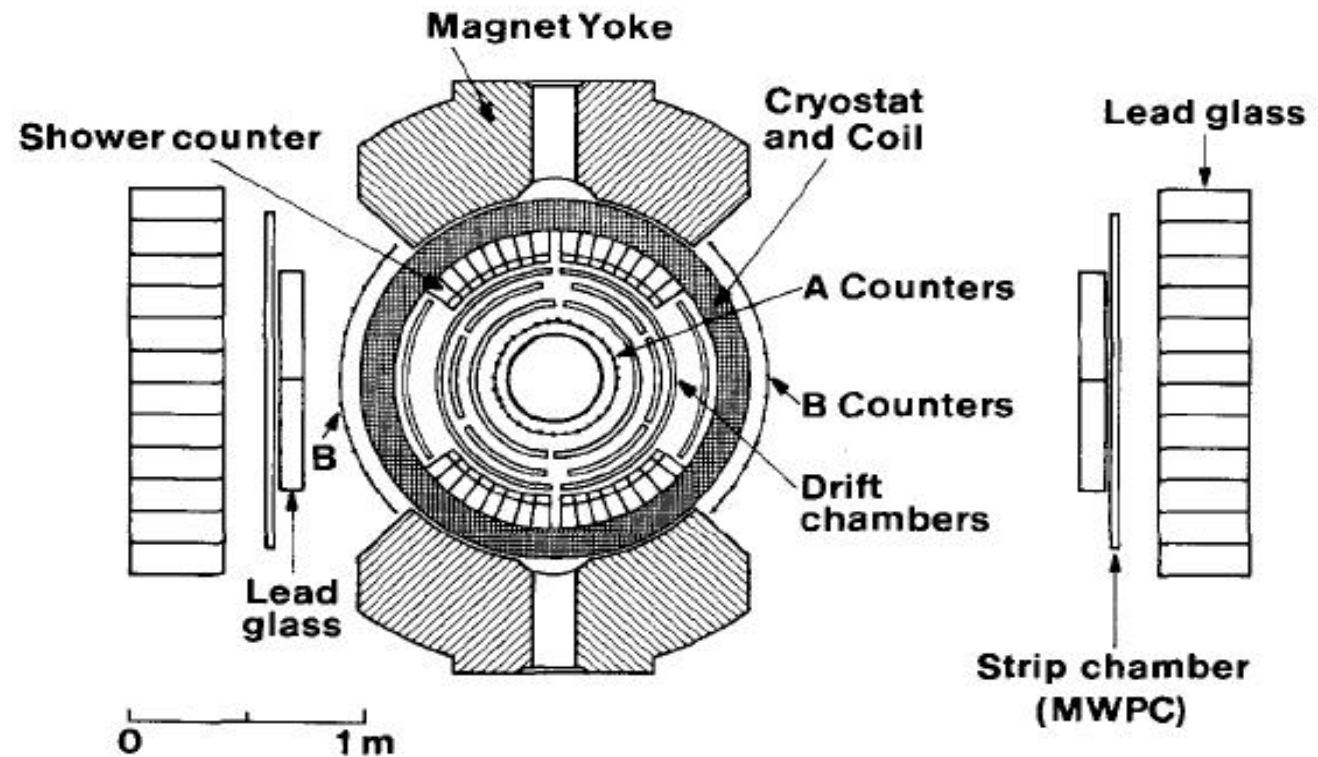
Fig. 2. The R-110 apparatus viewed along the beam axis.

(I couldn't resist showing this…)

Isolated photons setting the jet E-scale

Nucl. Phys. B327 (1989) 541
(Angelis et. al, inc. MJT…)

If in a back-to-back γ-jet pair
the photon is isolated, it is
a good measure of the total
jet energy (modulo initial k_T)

The complete disappearance of
γ-side partners with p_T>1.0 GeV
also suggests that Bremsstrahlung
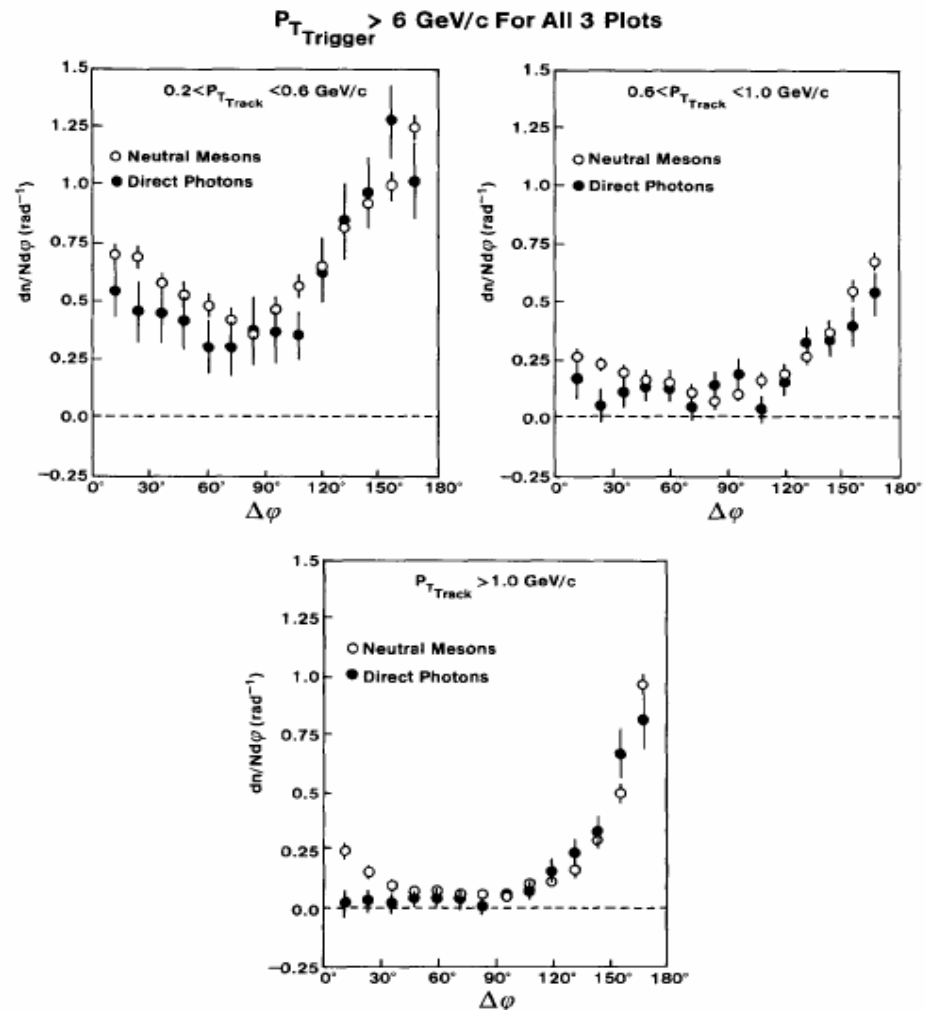is not a dominant source of photons
here

Fig. 15. Azimuthal distributions of charged associated particles for the direct photon and neutral meson samples (after background extraction) for $p_{T\,trigger}$ greater than 6.0 GeV/c and for three different $p_{T\,track}$ ranges.

Which graphs dominate direct γ production?

Another sign of the dominance
  of the Compton-graph:
  - for Compton the recoil particle
    is a quark
  - the proton is **uud** and **u** couples
    4 times stronger to photons
  → for photons the probability
    to get a positive hadron away-side
    is higher (except when we start
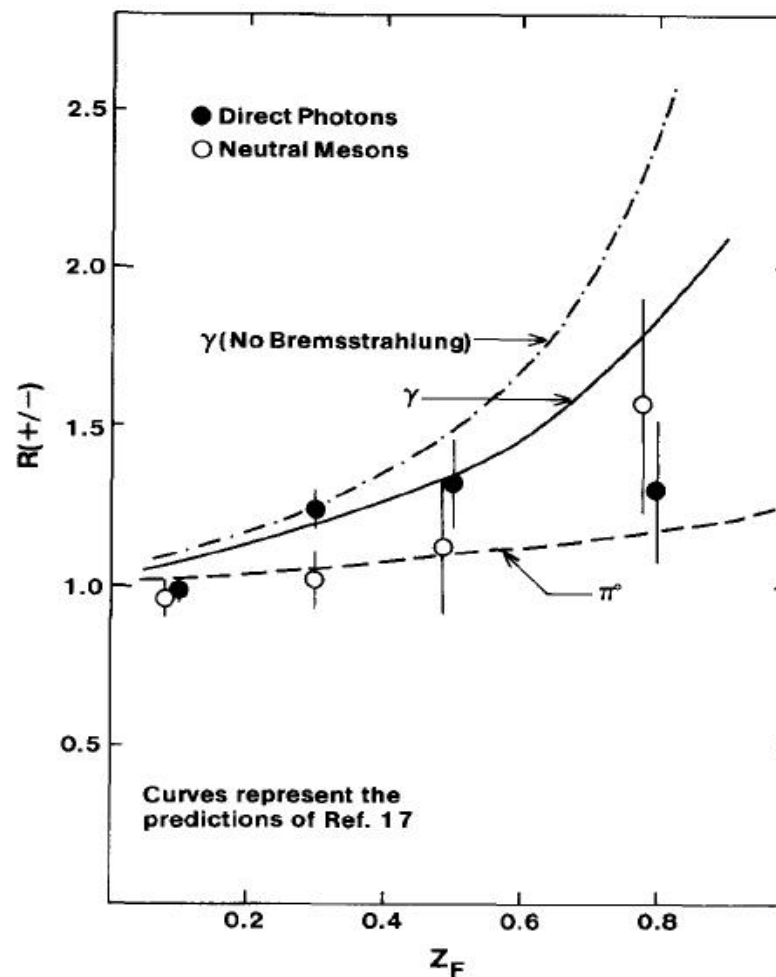   submerging in the sea)

Fig. 16. Ratio of the number of positive to negative charged hadrons in the away-side vs. z_F for the direct photon and neutral meson samples. Also shown are the predictions of ref. [17].

Nucl. Phys. B327 (1989) 541

Photon flow - direct, hadronic, …

WA98
Eur. Phys. J. C41 (2005) 287
Decreasing flow with increasing
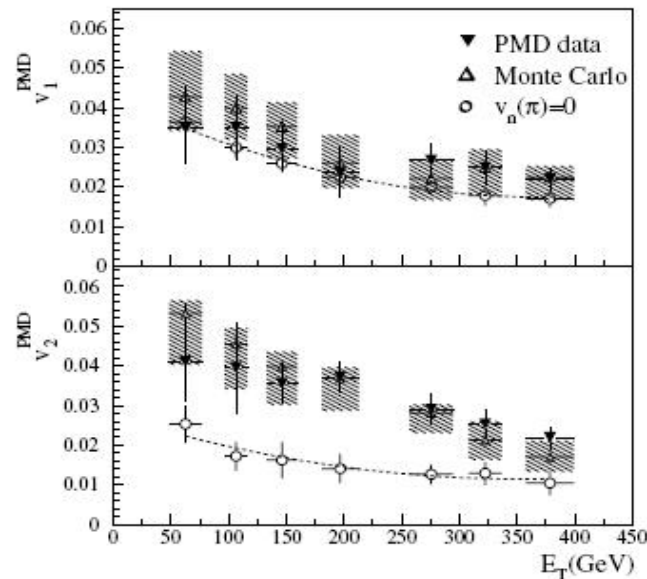 centrality
Photon v_2 not plotted directly

Fig. 6. a First order, v_1^{PMD}, and b second order, v_2^{PMD}, photon anisotropy coefficients in the pseudorapidity region $3.25 \leq \eta \leq 3.75$ for different centralities are shown by filled triangles. Statistical and systematical errors are added in quadrature and shown as bars on the filled triangles. Open triangles are the most probable values of v_n^{PMD} as expected from the simulation. The shaded regions indicate the simulation uncertainties as described in Sect. 5.4. The open circles show the calculated values of $v_n^{PMD}(v_n(\pi)=0)$ assuming an isotropic distribution of pions with the dashed curve indicating a smooth polynomial fit to the open points. Note, however, that $v_n^{PMD}(v_n(\pi)=0)$ can not be directly subtracted from the $v_n^{PMD}(v_n(\pi)>0)$ to obtain the anisotropy flow coefficents v_n, as explained in the text
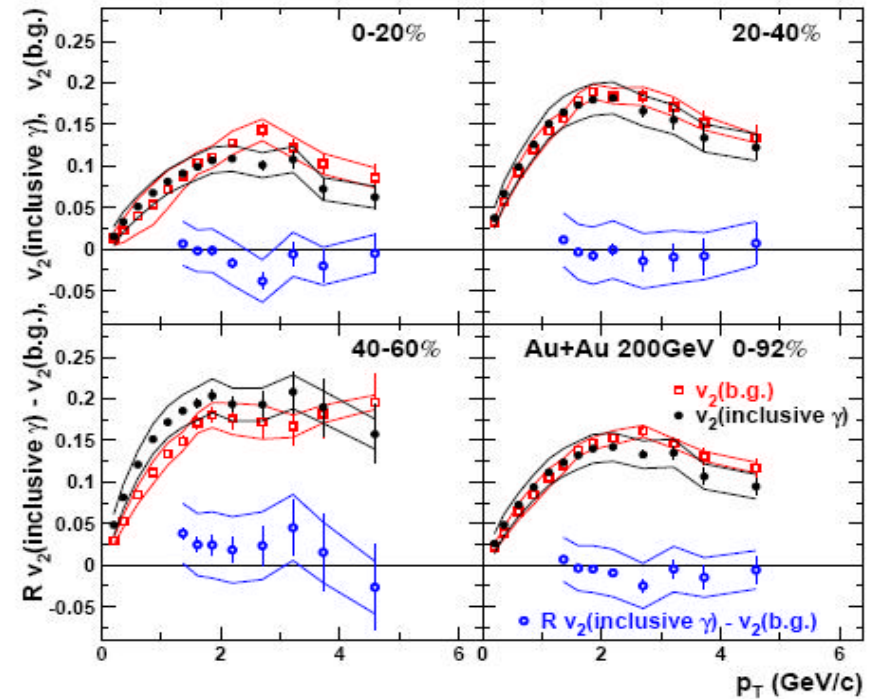

FIG. 2: (Color online) The measured v_2 of inclusive photons ($v_2^{inclusive \, \gamma}$, solid circle) and expected photon v_2 from hadronic decay ($v_2^{b.g.}$, open square). A subtracted v_2 quantity $Rv_2^{inclusive \, \gamma} - v_2^{b.g.}$ is plotted at the bottom of each panel (open circle), where $R = (N_{direct \, \gamma} + N_{b.g.})/N_{b.g.}$. The quantity corresponds to a product of the direct photon v_2 and a positive factor $R - 1$, ($v_2^{direct \, \gamma}(R-1)$).

Photon flow: the point

hep-ph/0508201
(Turbide, Gale, Fries)

Primary hard scattering photons
should be produced isotropically

Hadron decay photons should
inherit the flow of hadrons
(positive v_2)

If jet-plasma interaction is
significant source of photons,
negative (out-of-plane, $\pi/2$ shift)
flow is expected at high
momenta ("inverse optical
mechanism", the plasma is
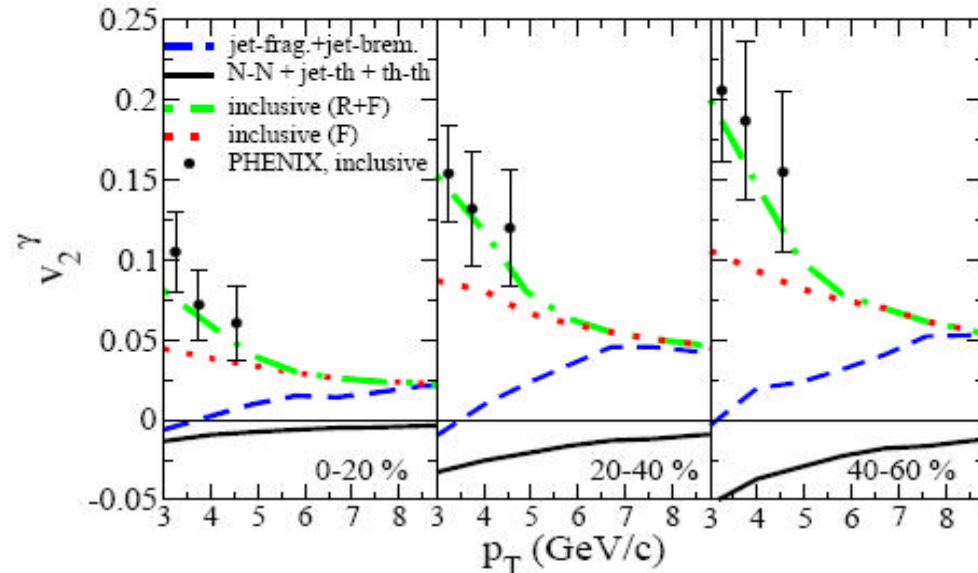thicker out-of-plane)

Note the p_T scale

FIG. 2: (Color online) v_2 as a function of p_T for Au+Au collisions at RHIC. The dashed line shows jet-fragmentation and induced bremsstrahlung only while the solid lines give jet-photon conversion, primary hard and thermal photons. The dotted line shows direct photons and the background from decay of neutral mesons coming from jets. The dot-dashed line adds photons from decay of recombined pions as well and can be compared to the inclusive photon v_2 measured by PHENIX [20].

Space-time evolution: photon HBT

Since π^0 decays at ~10^7 fm, Δq ~ few eV – no influence on measurable correlation
  - although HBT corr. of the π^0-s themselves may introduce fake correlation

Correlations at various p^T can map out
  space-time evolution (in principle…)

Δq ~ 1/R p_T range ~ 1/t
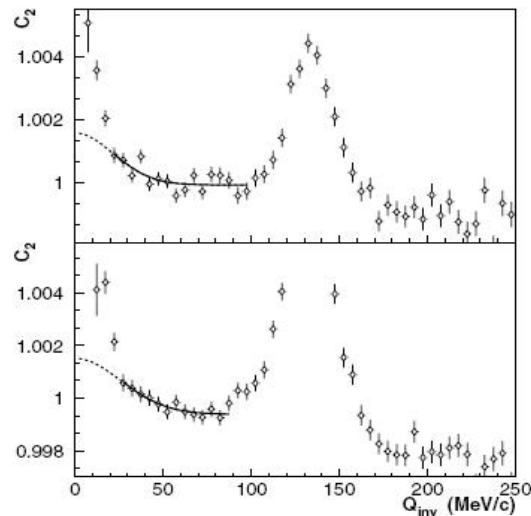
Exp: π^0 turned on (WA98)

FIG. 1. The two-photon correlation function for narrow showers with $L_{min} > 20$ cm (diamonds) and average photon momenta $100 < K_T < 200$ MeV/c (top) and $200 < K_T < 300$ MeV/c (bottom) fitted with Eq. (1). The solid line shows the fit result in the fit region used (excluding the π^0 peak at $Q_{inv} \approx m_{\pi^0}$) and the dotted line shows the extrapolation into the low Q_{inv} region where backgrounds are large.
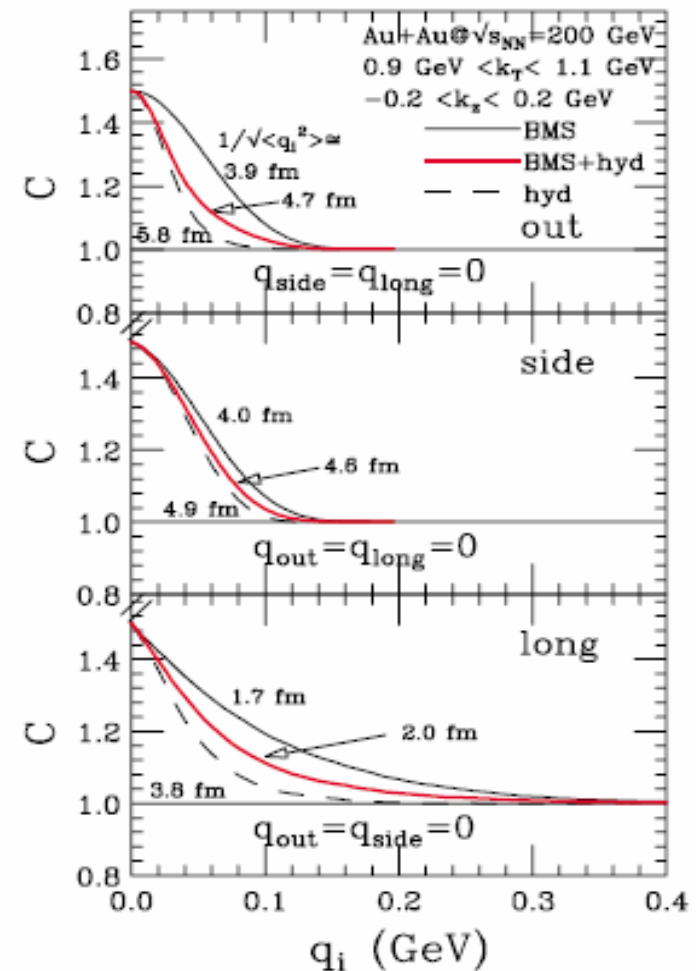
Theory: photons only

FIG. 3 (color online). Outward, sideward, and longitudinal intensity correlation of photons at 1 GeV, considering only PCM (BMS), only thermal (hyd), and all PCM + thermal photons (BMS + hyd).

Summary: disentangling processes (?)

We started out saying that photons (penetrating probes!) report on every stage of the collision; but it's a mixed blessing – can we ***disentangle*** those processes?

Sometimes we can. Examples (very far from complete list):

- testing LO processes using suitable ***hh*** collisions
- set the jet energy scale in γ-jet pairs with the photons isolated
- access system size at earliest times (high p_T HBT)
- medium properties via photons in the vicinity of a leading hadron
- medium properties via (out-of-plane?) photon flow
- medium properties via E-loss in jets vs jet-photon conversion γ
- temperature history of the collision (tall order!)
- access to gluon structure functions (when Compton dominates)
- …

If you ask for a signal, that encodes everything – watch out!
  You may get what you prayed for…